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ROI Coding Of Volumetric Medical Images with Application to Visualisation

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Abstract

This paper presents region of interest (ROI) coding of volumetric medical images with the region itself being three dimensional. An extension to 3D-SPIHT which allows 3D ROI coding is proposed. ROI coding enables faster reconstruction of diagnostically useful regions in volumetric datasets by assigning higher priority to them in the bitstream. It also introduces the possibility for increased compression performance, by allowing certain parts of the volume to be coded in a lossy manner while others are coded losslessly. Results presented highlight the benefits of the ROI extension. Additionally, a visualisation specific ROI coding case is examined. Results show the advantages of ROI coding in terms of the quality of the visualised decoded volume.

1. Introduction

Volumetric medical images are an invaluable tool for diagnosis and treatment planning, but also create problems (mostly due to their increased information content) in terms of their storage, communication and comprehension.

Storage of medical images is generally problematic because of the requirement to preserve the best possible image quality which is usually interpreted as a need for lossless compression. Effective storage and communication of such images also requires coding which can adapt to the bottlenecks that arise in applications such as telemedicine and remote- Internet - browsing. These requirements together with the need for fast transmission and browsing dictate the use of a coding method capable of progressive lossy to lossless coding.

One such very well known method is the SPIHT algorithm [1]. SPIHT uses spatial orientation trees and successive approximation quantisation in order to code the coefficients resulting from a previously applied wavelet transform. When reversible transforms are employed for the decomposition of the source image, like the S+P transform [2] or integer wavelet transforms [3], progressive lossy to lossless coding becomes possible, thus enabling the transmission of an image at various bit rates without the need for lossy compression of the original. This flexibility can be further enhanced by the introduction of 2D ROIs where greater "attention" is paid during the coding process [4] [5].

This can either mean that the ROI is coded losslessly while the rest of the image sustains some loss, or that the whole image is coded losslessly but the ROI gets higher priority in the bit stream.

For the case of volumetric medical images greater coding performance can be attained by exploiting the inter-slice correlation that exists in such images. For this reason three dimensional extensions of SPIHT for lossless compression of volumetric medical images have been recently proposed in [6][7] producing significantly better results than the original SPIHT. A 3D version of EZW [8] has also been presented in [9] as well as 3D SPIHT for video coding [10]. Other 3D wavelet coding methods include those in [11] and [12].

In this work a region of interest (ROI) extension is proposed for 3D SPIHT, with the region itself being three-dimensional, in order to increase the transmission flexibility and compression efficiency of the above coding method. With volumetric datasets the imaged area is usually big including information which is not always diagnostically necessary. It is highly likely for example that in the case of a volumetric image only a number of slices or a specific sub-volume will be diagnostically important with the rest of them providing the necessary anatomical context. The proposed extension allows the compression algorithm to reflect the variable importance of the volume in the resulting bit stream by giving the ROI a higher priority thus allowing it to reach a lossless level of reconstruction earlier than the rest of the volume. In addition the proposed ROI extension introduces the possibility for increased compression performance, by allowing certain parts of the volume to be coded in a lossy manner while others are coded losslessly. With visualisation being increasingly used for examining volumetric medical images (as opposed to simple slice by slice inspection) the case of visualisation specific ROI coding is also examined.

First we briefly describe how to get a 3D version of SPIHT from the original. We then describe the necessary modifications to the 3D-SPIHT for ROI coding, based on an analogous 2D case [5] and suggest methods of specifying a 3D ROI without adding a significant overhead. The case of specifying a visualisation specific ROI is separately described. Finally we demonstrate the coding benefits that the ROI extension brings to the transmission and storage of volumetric medical images as well as to their subsequent visualisation.

2. From 2D to 3D SPIHT

The modifications needed to obtain a 3D SPIHT from the corresponding 2D version affect the applied transform, the spatial orientation trees and the adaptive arithmetic coding. A 3D instead of a 2D integer wavelet transform is applied to the volumetric image. As in the case of 2D separable wavelet transforms, 3D transforms are obtained by sequentially applying the 1D transform across all dimensions (one axial and two trans-axial). The decomposition applied to the source volumes unlike [6] and similar to [9] was fully dyadic. The spatial orientation trees used with 3D-SPIHT are 3D with each pixel (voxel) of a non-root non-leaf node having as offspring eight adjacent voxels in a $2 \times 2 \times 2$ form one level below in the pyramid [10]. Arithmetic coding of the significance bits is also modified for the 3D case. Groups of $2 \times 2 \times 2$ voxels (instead of 2×2 pixels) are coded with a single symbol from a number of different adaptive models conditioned to the number of insignificant voxels and descendant sets in the group. A total number of 164 models are used.

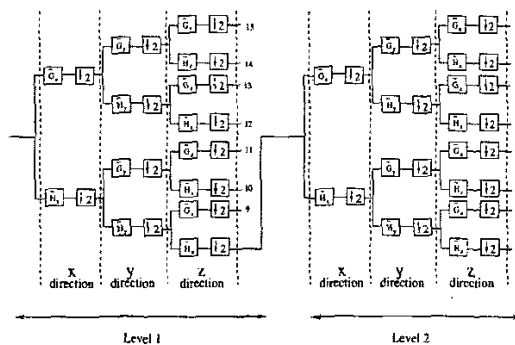


Figure 1. 3D dyadic decomposition with two levels.

One issue that comes up with the 3D version of SPIHT and the integer wavelet transforms mentioned in this work is the scaling that has to be applied to the transform coefficients in order for the transform to be approximately unitary. This is necessary in order to obtain a good rate distortion behaviour. As suggested in [2], the scaling factors that can be used are equal to $2/\sqrt{2}$ for the low pass coefficients and $1/\sqrt{2}$ for the high pass. For a 2D decomposition this results in multiplying each subband with factors of 2, which can be implemented as left bit shifts, and which preserve the reversibility of the transform. In the 3D case however the number of decompositions for each subband is not even unless a wavelet packet transform is employed as done in [6]. Scaling with the above factors for these subbands would result in coefficients which are not integer any more. However as suggested in [4], scaling by $2/\sqrt{2}$ and $1/\sqrt{2}$ the low and high frequency coefficients at each subband decomposition respectively is equivalent with scaling by 2 and 1, since multiplying both sets of coefficients with $\sqrt{2}$ doesn't change their relative importance.

3. ROI Coding With 3D-SPIHT

There are three issues that have to be addressed in order to add ROI coding functionality to SPIHT (both 2D and 3D). One is the selection of the wavelet transform coefficients that are necessary and sufficient for the lossless reconstruction of the ROI (the ROI lossless mask); the second issue is how to assign greater importance –priority– to these selected coefficients, and the third issue is how to specify the (3D in this case) ROI without adding a significant coding overhead.

3.1. Derivation of the ROI Lossless Mask

Although the region of interest is identified in the image domain it is the “wavelet image (volume)” – the coefficients of the wavelet decomposition – that is encoded and later decoded. Hence in order to assign a different priority to the ROI compared to the rest of the volume and/or guarantee the lossless reconstruction of the ROI, the coefficients that affect the ROI have to be identified [5][6]. To do that a three dimensional bitmap mask, named the ROI lossless mask, is maintained at the encoder indicating these coefficients. This mask undergoes a similar transformation to that of the forward wavelet transform of the image, where at each step the necessary coefficients for the perfect reconstruction of the ROI at the current level of decomposition are identified [5][7]. The inverse wavelet transform is consulted at each decomposition and based on the region of support of the synthesis filters (or the lifting steps of the inverse transform) those coefficients that will be necessary at the decoder for the perfect reconstruction of the ROI at the current level are selected. For example, assuming a 1-D one-level decomposition using the 5/3 integer transform, which has 3 low pass and 5 high pass synthesis taps, the low pass $-L(n)-$ and high pass $-H(n)-$ coefficients that are necessary for the reconstruction of the original samples $X(2n)$ and $X(2n+1)$ are $L(n)$, $H(n-1)$, $H(n)$, $L(n+1)$ and $H(n+1)$. The 3D-ROI lossless mask is obtained with iterative application of the 1-D decomposition stages. It is obvious that the mask expands with each decomposition. In the 3D case this expansion takes place in the Z (slice) direction as well as the X and Y directions of the 2D case. Transforms with short filters (e.g. the 5/3) result in fewer coefficients being included in the ROI lossless mask which can lead to faster reconstruction of the ROI.

3.2. Specification of the ROI Priority

In order to assign greater priority to the ROI, the coefficients of the ROI lossless mask are scaled up through a fixed number (S) of left bit shifts (each left bit shift corresponds to scaling up by a factor of 2) [5]. The larger the number of left bit shifts, the greater the emphasis placed on the ROI and the faster the lossless reconstruction of it.

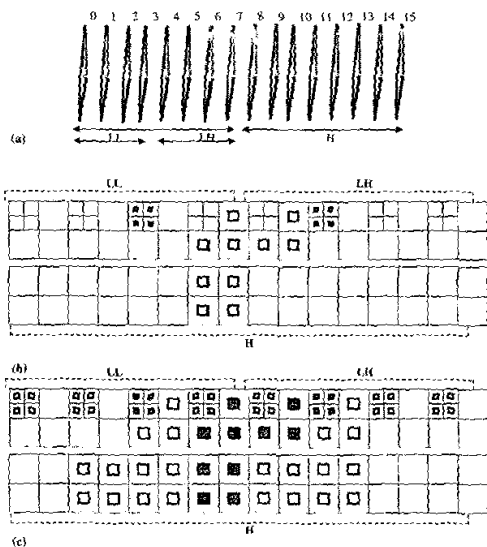


Figure 2. ROI lossless mask for a square ROI of size 101x101 covering slices 6,7,8, of a 256x256x16 size volume using the integer 9/7M transform and a 2-level classic dyadic decomposition. (b) Spreading of the ROI in different subbands without expansion. (c) ROI lossless mask with extra coefficients shown in light grey.

As the algorithm checks for significant coefficients at each bit plane it will only code ROI coefficients for all the bit planes above the current (before the shifts) threshold. All trailing ROI zero bits at the last S bit planes are ignored by both encoder/decoder.

3.3. Description of a 3D ROI

The amount of additional information that needs to be sent to the decoder in order to enable decoding, is the description of the ROI and the speed of reconstruction (the number of shifts applied to the ROI). Having got this information the decoder can reconstruct the mask and scale the ROI coefficients down by ROI-shift bits. It is important for the coding performance of the algorithm that this additional information is kept compact. This means that the ROI is specified in a way which will not add a significant overhead to the final bit stream. When regular shapes are used for the description of the ROI the extra bits added to the coded file in order to describe the ROI are minimal. For example a cylindrical shape can be used to specify a circular ROI spreading to multiple slices. The centre, radius and height of the cylinder have to be included in the header of the coded volume adding minimal overhead to the bitstream.

A flexible way of specifying a 3D ROI is through the use of volume cropping. A number of different three-dimensional ROIs can be created by means of specifying a minimum and maximum value for the X, Y and Z dimensions along with the type of cropping. The

information that has to be included in the header is that of the min and max X,Y,Z values and the type of cropping used. For arbitrarily shaped ROIs one can use a method similar to the MAXSHIFT method specified in JPEG2000 [13]. By scaling the ROI coefficients so that the minimum coefficient magnitude belonging to the ROI is larger than the maximum non-ROI coefficient magnitude, the decoder can easily identify which coefficients belong to the ROI - any coefficient found significant during the first ROI shift bitplanes - and scale them down appropriately.

4. Visualisation Oriented ROI Description

Depending on the parameters of the subsequent visualisation, the voxels of a volumetric medical image can have different importance in terms of how they affect the result of the visualisation process [14]. Based on this importance voxels can be classified in two (or more) categories. In this paper the classified as important voxels, are used to form a (three dimensional) region of interest (ROI). The volume is then coded with 3D ROI SPIHT which gives higher priority to the coefficients that affect the quality of the produced image at any desired volume reconstruction rate. The classification process used to form the ROI is briefly described below for two visualisation methods, iso-surface rendering with the Marching cubes algorithm [15] and direct volume rendering with ray casting [16].

4.1. Iso-Surface ROI.

Given an iso-value, the marching cubes algorithm reconstructs the specific iso-surface by determining all the edges of cells in the volume that intersect the iso-surface. The surface is approximated with triangles whose vertices position must be calculated. This is done by means of linear interpolation from the value of two edge incident voxels for all three edges of each triangle. Immediately it becomes obvious that all such edge voxels must be included in the ROI. The produced triangles are then shaded using normal vectors calculated for each vertex through linear interpolation of the normal vectors of the edge incident voxels. In turn these voxel vectors are approximated by gradients which are computed as central differences from the 6-neighbors of these voxels. Hence these additional 6-neighbor voxels have to be included in the ROI for a correct iso-surface reconstruction. Figure 3 depicts all the voxels that need to be included in the ROI for a single intersecting cell edge.

4.2. Ray Casting ROI.

With ray casting the importance of voxels is primarily determined by the opacity transfer function used to map the different materials (density values) encountered along the rays. Assuming a model similar

to the one in [16], the opacity transfer function is defined by an opacity value a_m and four density values $[d_0, d_1, d_2, d_3]$. Any voxel with density value between d_0 and d_3 , has a part to play in the creation of the final projected image. If gradients are used to emphasize voxels close to boundaries, then they will also have to be considered when checking the importance of voxels. The final projection image is formed by accumulating shaded colours and opacities at sample points along each ray cast from the image plane. Any given sample point along the ray will influence the result if at least one of the voxels of the respective intersecting cell has a value in the opacity range mentioned before. In that case a shaded colour will have to be calculated for the sample point, requiring the calculation of a normal vector at that point, which in turn requires tri-linear interpolation of the gradients of all voxels in the cell. Hence all the voxels in a cell and their 6-neighbors will have to be included in the ROI whenever one or more of its voxels is found to be important.

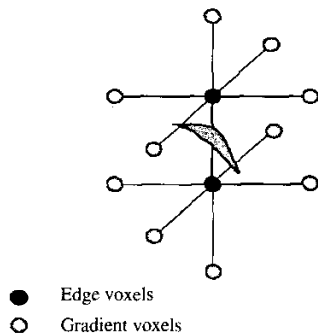


Figure 3. Iso-surface ROI voxels [14].

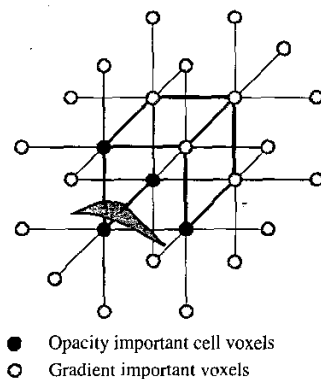


Figure 4. Ray casting ROI voxels [14].

5. Coding Results

Coding results are first presented for two volumetric medical datasets, one CT and one MR with sizes $256 \times 256 \times 128$ and $256 \times 256 \times 64$ respectively. This set of results assesses the ROI reconstruction speed. In both

cases the 5/3 integer wavelet transform was used with 5 and 4 levels of decomposition. Volume cropping was used for the specification of the ROIs. The second set of results is an example of lossless on the ROI lossy elsewhere compression that highlights the increased compression performance that can be had with 3D-ROI-SPIHT, by allowing a small amount of loss for the background. Finally the last set of results demonstrates the visualisation oriented ROI case. Results for this case are presented for a CT dataset of the head, from the visible human project. The size of the dataset is $256 \times 256 \times 156$ with 8 bits per pixel. The 5/3 integer wavelet transform was again used for the results with a coding unit of 32 slices and 3 levels of decomposition.

5.1. ROI Reconstruction Speed.

For the CT dataset, a ROI was specified using the inverted fence cropping type with minimum and maximum values for the X, Y and Z dimensions of 145-255, 115-150, and 0-70 respectively. The created ROI includes all the voxels that do not belong in any of the above intervals and amounts to 21.6% of the volume. A 3D rendering of the ROI is shown in figure 5c. Results are presented with the ROI having a high priority ($S=13$) a medium priority ($S=9$) and a low priority ($S=5$), with 19 bits being the maximum significance threshold (including scaling for making the transform approximately unitary). Table 1 summarizes the results. The PSNR vs. bit rate performance for the ROI only and the whole volume are plotted in figures 5a and 6b. Results without ROI coding ($S=0$) (that is with 3D SPIHT) are also included in the graphs. Similarly a ROI sub-volume of size $145 \times 221 \times 21$ (16% of the volume) was specified for the MR dataset. The sub-volume can be seen in figure 6c.

As expected, 3D-ROI-SPIHT allows considerably faster lossless reconstruction of the volume of interest at the expense of slower PSNR improvement for the rest of the volume. The inclusion of the ROI and the necessary shifting of the ROI coefficients result in only a slight increase of the lossless bit rate for the whole volume.

TABLE 1: CT Volume ROI results.

ROI Priority	ROI lossless rate (bpp)	PSNR at ROI lossless rate (dB)	Lossless bit rate (bpp)	Increase of bit rate (%)
S=0	2.360	Lossless	2.360	-
S=5	1.01	42.57	2.409	2.08
S=9	0.72	30.66	2.412	2.20
S=13	0.69	25.33	2.415	2.33

TABLE 2: MR-Chest Volume ROI results.

ROI Scaling	ROI lossless rate (bpp)	PSNR at ROI lossless rate (dB)	Lossless bit rate (bpp)	Increase of bit rate (%)
S=0	2.124	Lossless	2.124	-
S=5	0.65	44.90	2.227	4.85
S=8	0.52	38.78	2.232	5.08

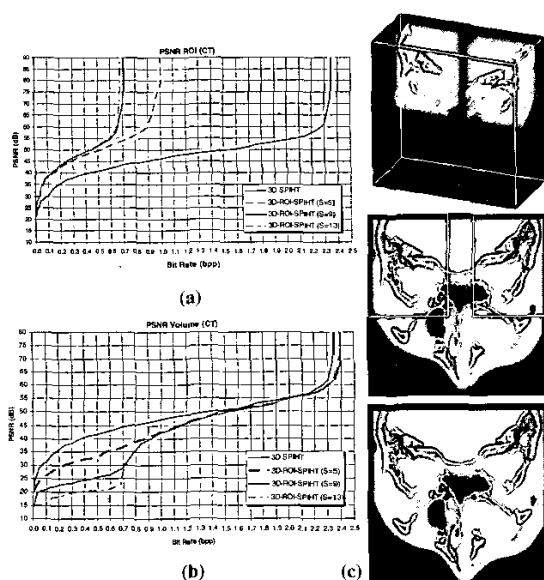


Figure 5. CT dataset: a) ROI PSNR and b) volume PSNR for the ROI shown at the top of the right column c) top - 3D ROI, middle - slice 78 of volume reconstructed at 0.72 bpp with lossless ROI marked, bottom - original slice.

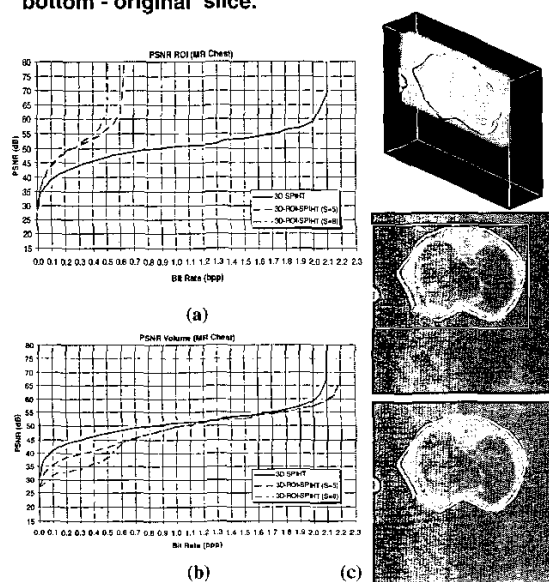


Figure 6. MR dataset: a) ROI PSNR and b) volume PSNR for the ROI shown at the top of the right column c) top - 3D ROI, middle - slice 30 of volume reconstructed at 0.52 bpp with lossless ROI marked, bottom - original slice.

5.2. Increased Compression Performance.

With volumetric datasets the imaged area is usually big including information which is not always diagnostically necessary. A typical example is that of MR images of the head where depending on the task ahead, the area of the brain might be the only diagnostically relevant area (the ROI). Assuming a prior segmentation of the

volumetric image one could store the dataset at a rate that would ensure lossless reconstruction of the ROI and a high PSNR for the rest of the volume that provides the necessary anatomical context. An example of such a case is given below. 32 slices of a 256x256x160 sized MR volumetric image of the head are coded with the 5/3 integer transform and 3 levels of decomposition. The MAXSHIFT method is used to convey the ROI (the brain area) to the decoder, ($S=16$ with 15 being the maximum significance threshold). The ROI becomes lossless at 0.83 bpp with the volume PSNR being very low at this rate (15.97 dB). If the image is stored at 1.7 bpp then the average volume PSNR becomes 50.26 dB high enough to be considered visually lossless. The compression ratio in that case is 4.706 which compared to the standard 3D-SPIHT (compression ratio 2.96, rate 2.69 bpp) represents a 63 % decrease in storage size.

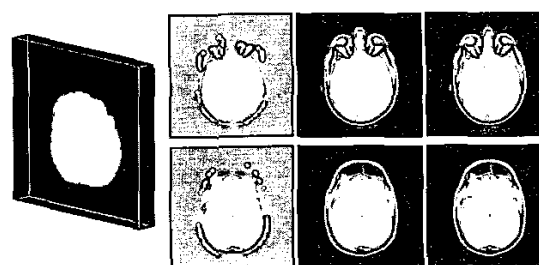


Figure 7. Lossy / lossless compression of MR-Head dataset. a) 3D ROI b) 2 volume slices with ROI lossless at 0.83 bpp; c) same slices at storage rate of 1.70 bpp; d) lossless slices at 2.69 bpp.

5.3. ROI Coding for Visualisation.

An iso-value of 70 corresponding to skin was chosen for the iso-surface results. The number of voxels included in the ROI for the specific iso-value represents 4.89 % of the volume. PSNR results for the ROI are shown in figure 8. Images of the reconstructed surfaces with Marching Cubes are also shown in figure 8 at various bit rates including their PSNR values (PSNR calculation based on image of iso-surface reconstructed from the original data). It can be seen that the quality of the reconstructed surfaces is higher for the ROI case, benefiting from the higher PSNR of the relevant voxels. For ray casting, the case of visualising skin and bone with the skin being transparent was examined. The selected - ROI- voxels represent 33 % of the volume. Again the benefit of the ROI extension is reflected in the quality (PSNR) of the projection images (figs. 8,9).

6. Conclusion

In this paper we have proposed and demonstrated the benefits of adding ROI capability to 3D-SPIHT for coding of volumetric medical images, in terms of faster ROI reconstruction and increased lossy/lossless coding performance. We have also shown the benefit of ROI coding for the visualisation of such images.

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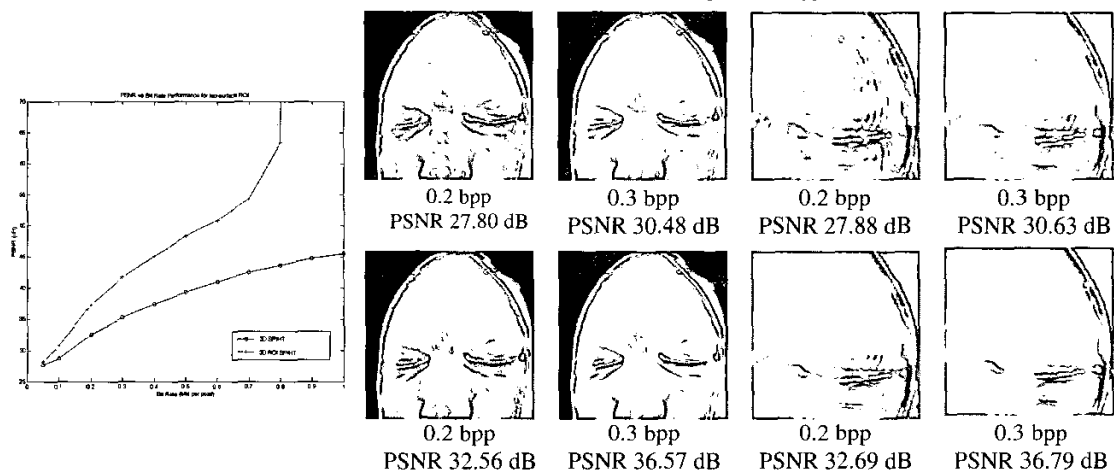


Figure 8. Iso-surface ROI coding results. Top row 3D SPIHT – bottom row 3D-ROI-SPIHT

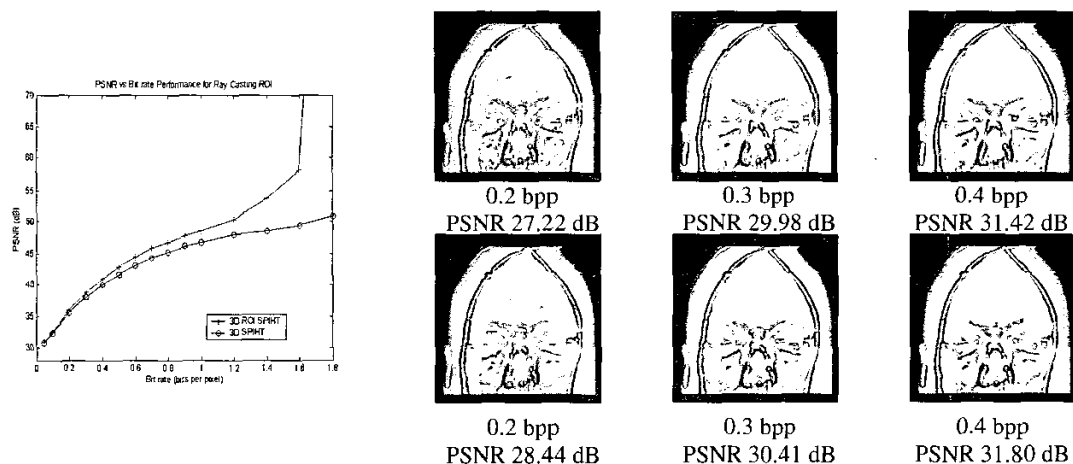


Figure 9. Ray casting ROI coding results. Top row 3D SPIHT – bottom row 3D-ROI-SPIHT